A MINI-ATLAS OF OCEANIC WATER MASSES IN THE PERMIAN PERIOD

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In today's oceans, surface water masses exert a controlling effect on biogeographic provinces, climate-sensitive sediments and organic productivity, so it is important to understand the factors that generate and differentiate these water masses. A generalised temperature and salinity map of the Recent, with related effects like upwelling, sea ice, and surface runoff, has been compiled in a new attempt to define marine climates. Present-day climate-sensitive sediments are included to test their reliability as water mass indicators in the geological past. Then, reversing the approach, water mass maps for the nine Permian stages have been reconstructed from the sediment types as well as from biogeographic considerations. It is clear from the Present-day water mass map that geographically or bathymetrically restricted seaways are more likely to reflect local climate and be distinct from open ocean water masses in salinity or temperature. Our Permian maps have been prepared with this duality in mind: epeiric seaways are portrayed with the most differentiated water masses, while narrow continental shelves are generally similar to adjacent oceanic areas.

PRESENT-DAY WATER MASSES

The term, water mass, is herein used as the marine equivalent for the terrestrial climate zone, or biome, and this seems appropriate because temperature and salinity effects in the oceans generally seem to have sharp boundaries, in contrast to the land surface climate zones which possess more gradual transitions. Water masses have been defined in a variety of ways, but many published maps derive from the classic work, 'The Oceans' (Sverdrup et al. 1942), which shows a limited number of primarily ocean basin water masses characterised by specific 'temperature-salinity characteristics' and defined along their margins by major convergences or divergences resulting from density differences. By analogy with the atmosphere, these boundaries may be referred to as 'fronts' and come in a variety of scales, including estuarine fronts, shelf-break fronts, and upwelling fronts (Mann & Lazier 1991). The more local scales are applicable to the geological past because they affect settings typically preserved in the stratigraphic record.

In 'Marine Zoogeography', Briggs (1974) used the major oceanic convergences to delimit latitude-related 'Surface Temperature Regimes' and observed that the north–south trending continents provide longitudinal barriers for the various biogeographic 'regions'. He went on to opine that, within regions, 'minor barriers to gene flow exist that, over periods of time, have resulted in the formation of local endemic species', and he identified these as provincial level boundaries. Briggs based his zoogeography on fishes, but concluded that the observed endemic patterns were common to other major groups. Most palaeontologists probably reflect these views, but we point out that sharp salinity changes and surface productivity levels also must play a major role in biogeographic differentiation, and indeed may have been the only factors when meridional land barriers were less effective. A better model for the faunas of the geologic past may be the 'Large Marine Ecosystem unit': 'LMEs are relatively large regions, on the order of 200 000 km^2 or larger, characterised by distinct bathymetry, hydrography, productivity and trophically dependent populations' (Sherman 1993). About 50 of these units have been defined for the shelf seas, and include ecosystems on the scale of the Great Barrier Reef and Indonesian Seas.

The water mass approach is also relevant economically because certain types of deposits form under very specific marine conditions; these include evaporites, phosphorites and oil source rocks. The evaporites, including halite and gypsum, are deposited in areas where evaporation exceeds precipitation, and where a level of isolation from the ocean is established. Today, such areas are mainly limited to lagoons, but in the Permian, evaporite basins achieved scales of millions of square kilometres (Ziegler et al. 1997). At the opposite end of the spectrum, basins with a positive precipitation balance may be sites for organic rich muds and 'estuarine circulation' (Demaison & Moore 1980; Hay 1995). Here, nutrient-rich waters converge from surface runoff and also inflow from the sea creating a 'nutrient trap' and enhancing surface productivity, while low-density brackish surface waters contribute to stratification of the water column, in turn limiting oxygenation of the bottom waters. Upwelling water masses also contribute to high surface productivity through nutrient recycling and have been implicated in oil source rock formation and phosphorite deposition (Parrish 1982, 1995).

We have developed an eight-fold classification of Present-day water masses of the oceans using particular salinity, temperature and productivity related effects (Table 1). Our water mass base map is shown together with sediments reflecting these three parameters; Fig. 1 shows peats and evaporites for comparison with the contours reflecting salinity, Fig. 2 has reefs versus the potential for ice-rafted debris representing extremes on the temperature scale, and Fig. 3 illustrates the distribution of phosphorites and oil source rocks for correlation with the potential sites of organic productivity, whether associated with upwelling or estuarine type water masses. The water mass boundaries are based on a conglomeration of parameters determined from ocean-scale atlases showing monthly or at least seasonal maps. The contours were chosen rather arbitrarily because it is difficult to select particular isotherms or isohalines that universally mark the rapid changes that would reflect transitions in water mass types. Maps representing opposite seasons were first prepared and examined for the seasonal changes in the position of the various water masses. Then, the extreme, generally winter, conditions were used in the composite base map for Figs 1–3 because cold temperatures are generally limiting for marine organisms. It must be emphasised that the boundaries of the water masses, however defined, change constantly so their mapped positions serve only as a guide to the general patterns. The following sections provide additional details on each of the eight water masses.

1. Wet Tropical. Water masses of the wet tropical zone are defined as having relatively brackish conditions with salinities below 32‰ (average surface salinity of the ocean is about 34.5‰). Such areas typically have high runoff from nearby land with accompanying high turbidity. The plumes from major deltas, like the Amazon and Niger, fall in this category as do the shallow equatorial seaways typified by the Indonesian region where the rainfall associated with the Intertropical Convergence Zone (ITCZ) is concentrated. The Bay of Bengal brackish conditions extend over the deep ocean due to the high river runoff and low mixing in a regime of light wind activity (Tomczak & Godfrey 1994). There is a rather vague correlation of peat with low salinity only for restricted seas like Indonesia (Fig. 1). By contrast, peat along the eastern coast of Brazil is associated with normal to high salinity showing that, along narrow shelves, coastal precipitation has little influence on the salinity of the marine environment. Organic rich shales (Fig. 3) seem not to be associated with the wet tropical water masses at the present time, but they almost certainly were in the geological past (e.g. the Permian of South China and the Jurassic of the Arabian Peninsula). We can surmise this because of the dual correlations of these source rocks with low palaeolatitudes, and of the general coincidence of the ITCZ with the Equator today. Our view is

Coastal climate zone	Water mass essentials	Geological recognition	End-member example
Glacial	Surface permanently frozen	Marine till	Ronne Ice Shelf
Cold Temperate	Winter ice floes	Dropstones, rhythmites	Labrador Current
Wet Temperate	Brackish surface waters	Temperate peats, organic-rich shales	Baltic Sea
Temperate	Mixed water column	Clastics	Kiroshio Current
Cool Subtropical	Upwelling currents	Organic-rich shales, phosphorites, cherts	Humboldt Current
Dry Subtropical	High evaporation	Gypsum, halite, sabkha facies	Persian Gulf
Tropical	Deep light penetration	Carbonates, oolites coralgal reefs	Bahamian Platform
Wet Tropical	High continental runoff	Tropical peats, muddy sediments	Indonesian Seaways

Table 1. Water mass classification.

that these geographic settings, if associated with restricted basins, would be productive because high rainfall would result in estuarine water masses.

2. Tropical. Tropical water masses are herein limited by the 20°C winter isotherm (Briggs 1974). Additional requirements are that salinity is normal and the water is clear due to a lack of sediment or plankton in the water column. In low latitudes, light penetration to the bottom can occur because the zenith angle of the sun is sufficient for refraction to the sea floor throughout the annual cycle (Ziegler et al. 1984). This warms the water and allows for bottom productivity and carbonate build-ups in areas of good circulation, due mainly to the profusion of calcareous secreting algae and hermatypic corals. Our reef distribution (Fig. 2) is mainly confined to the Tropical and the Dry Tropical water masses as defined. In our experience, this is true of the geological past, such that carbonate build-ups rarely plot above 35° palaeolatitude for areas whose positions are well-constrained by palaeomagnetic data (Hulver et al. 1997). Non-tropical carbonates can be developed poleward of reef trends where terrigenous sediment dilution is insignificant (Nelson 1988), but Bahamian-type carbonates with reefs, algal mats and oolite shoals are the characterising features of the Tropical water masses.

3. Dry Subtropical. Areas with salinities above 37‰ (yellow shading on Figs 1–3) are under the influence of a strong negative precipitation minus evaporation balance and do possess evaporite deposits in coastal lagoons. Admittedly, such indicators also occur along upwelling coasts, and are not uncommon along coasts characterised as having Mediterranean or Savannah climates, so a generally negative precipitation situation is adequate for evaporites. A subdivision of the Dry Subtropical water mass with above 42‰ salinity (red shading on Figs 1–3) is shown, but is only seen in the Kara Bogaz Gulf on the east side of the Caspian Sea. This subdivision is proposed mainly for the geological past when broad evaporative seas existed in the subtropical zone. Areas like the Red Sea are not suitable for oil source rock formation because the saline waters generated in shallow waters form density currents which convey oxygen to the depths of the basin.

4. Cool Subtropical. This category is reserved for upwelling zones which are mainly limited to the subtropical belt where the consistency of wind direction and strength is available to drive Ekman transport. Our maps show upwelling for opposite seasons and were compiled from a variety of information ranging from temperature anomalies to organic productivity (Binet & Marchal 1993; Gordon 1967; Ittekot et al. 1992; Parrish et al. 1983; Sharma 1978; van Andel 1964; Zijlstra & Baars 1990). Many organic rich muds and phosphorites are associated with these upwelling zones (Fig. 3), especially along the eastern boundary currents of the Atlantic and Pacific oceans. The Arabian Sea is an interesting case because organic rich muds and upwelling are common there, but do not generally overlap in map distribution. Here, the upwelling does generate high organic productivity, the decay of which consumes the oxygen in this region. This allows for preservation of organic matter on the sea floor, which is isolated from the deep oxygenated waters of polar origin by sills related to sea floor spreading.

5. Temperate. This category ranges from the 20°C to the 0°C isotherms and is simply reserved for the broad temperate seas with average salinity. There seems to be no particularly distinctive climate indicator of this zone, although peats are quite common due to the low evaporation rates in mid to high latitudes.

6. Wet Temperate. As in the case of the Wet Tropical, this category is defined by brackish conditions, with salinities below 32‰ and, in extreme conditions like the Baltic and Black seas, by salinities below 27‰ (dark brown color on the maps). These conditions are especially well developed in geographically or bathymetrically restricted basins associated with high rainfall zones. Peats are characteristically developed around the margins and organic rich muds are common in the centre, again due to the estuarine circulation induced by the fresh water cap effect.

7. Cold Temperate. These water masses are defined by the extent of sea ice in the winter season and this corresponds closely with the 0°C isotherm (Zwally et al. 1983; Parkinson et al. 1987). A high degree of asymmetry is observed in the Northern Hemisphere with respect to both Atlantic and Pacific oceans. This is because the high pressure cells over North America and Eurasia drive poleward currents (like the Norwegian Current) on the west sides of the continents and the Equator-ward currents (Labrador Current) on the east sides of the continents. Cold Temperate ice-dominated seas reach low latitudes (45°) on the east sides of the continents while the ice flows are confined above 80° by the Norwegian current, even in winter. The seasonal variability in air and sea surface temperature is at a maximum along the east sides of continents due to outflow of cold continental air, causing a stressful existence for organisms living there. In the Southern Hemisphere the sea ice extends about 1000 km from Antarctica in the winter, but virtually disappears in the summer, making this an extremely variable environment (Zwally et al. 1983). Diamictites would be indicative of this environment in the fossil record.

8. Glacial. Permanent ice floes, like most of the Arctic Ocean, or the Ronne and Weddell Ice Shelves, constitute this environment. Tills could be expected along mountainous coasts of these regions. The Glacial and Cold Temperate Water Masses today are generated by outflow of cold air mainly from ice sheets, so the question arises as to their existence during periods of the geological past when continental scale ice domes were lacking. The situation in the Northern Hemisphere is complicated by the confined nature of the Arctic Ocean; winds cannot effectively disperse the ice on an annual basis as happens in the Southern Hemisphere. From the meteorological point of view, the northern continents together with the Arctic Ocean constitute a polar supercontinent, producing frigid climates atypical of the geological past (Ziegler 1998).

PERMIAN WATER MASS RECONSTRUCTIONS

Water Mass maps have been prepared for the nine stages of the Permian (Figs 4–12) and are based on the palaeogeographic maps of Ziegler et al. (1997). They have been reconstructed from the climate-sensitive sediment types already discussed as well as from facies maps in the literature. The sediment database has 1200 fully documented entries which provide information on location, age, environment and literature reference for each point. This database differs from our previous efforts in that it covers all the stages of the geological period under consideration, but it is limited to specific rock types. The age control is provided in terms of local as well as international stages (Jin et al. 1997) to allow for future changes in our understanding of the correlation of these units. The climate-sensitive database (including the Recent) is available on request from the senior author.

There are a number of caveats in reading the Permian maps presented here. The continental positions are being refined based on a thorough reassessment of the ages of the formations from which the palaeomagnetic determinations were obtained. Secondly, the shoreline positions were taken from Ziegler et al. (1997); these represent average positions for each of four intervals and because of this, some marine data points may appear in the wrong environment. Thirdly, the correlation of Permian sections around the world is in a state of flux. Finally, the Permian stages average about five million years long, and significant changes in climate can occur within a stage, due for instance to Milankovitch effects, allowing for the superimposition of data representing different climate settings.

Special attention should be given to the broad epeiric seaways because this is where the climate-sensitive sediments tend to be concentrated. The epeiric seas would have been isolated enough from the open oceans to develop distinctive water masses. Also of general interest is the fact that Pangaea drifted north about 15° in the Permian, so climate changes noticed in many of the basins are due to this change in palaeolatitude (Ziegler et al. 1997). In the following discussion, the Permian water mass development is described on a region-by-region basis, proceeding from south to north. The details provided herein are brief and just a few key references are provided because the palaeogeographic details have been published (Ziegler et al. 1997) and a comprehensive atlas on the Permian is in preparation.

Sydney and Bowen Basins. These eastern Australian basins remained at about 60° south throughout the Permian where Glacial climates were widespread in the earliest Permian stage as in many other Gondwanan areas. Following this, Cold Temperate conditions, as evidenced by dropstones and restricted benthic faunas and coastal floras, persisted through the Early Permian and just into the Middle Permian (Dickins 1996; Shi & Archbold 1996; Retallack 1980). Glacial activity is not implicated, at least at coastal plain elevations, and seasonal ice is thought to have rafted the debris into the basins. The persistence of cold conditions along the eastern continental margin is similar to the Present situation (Fig. 2) as it is here that flow, like the Labrador Current, transports sea ice to lower latitudes, and that the outflow of continental air is greatest in the winter.

Parana and Karoo Basins. These basins of southern South America, southern Africa and Antarctica were interconnected as indicated by similarities in the microstratigraphy and faunas (Oelofsen & Araujo 1983; Collinson et al. 1992). Early Permian marine faunas became endemic, then disappeared suggesting that the seaway became progressively isolated from the ocean during the Permian (Newell & Runnegar 1970). The exact connections with the ocean are unknown but it seems likely that they were severed by the convergent tectonics along the southern margin of Gondwana (Cape Orogeny, etc.). Diamictites are present during the first three Permian stages, but alternate with interglacial intervals, including an interval of phosphorites directly on top of tillites in the Sakmarian (Fig. 5; Buhmann et al. 1989) of South Africa. These may represent 'ice-margin upwelling' conditions (Hay 1995). The Irati and Whitehill oil shales follow (Fig. 7; Cole & McLaughlin 1991; Zalan et al. 1991) although the correlation with the late Lower Permian is uncertain and subject to change. We reconstruct brackish conditions in this seaway during most of the Permian in view of the coals and low diversity faunas, although by the late Permian, the Parana region was clearly drifting into the subtropics and has indications of arid conditions. Of course, brackish conditions can exist in dry regions (e.g. the Present-day Caspian Sea) if the supply of fresh water from adjacent regions is sufficient, and this particular basin extends over 40° of latitude.

Western Australia and northern India. Scattered occurrences of phosphorites (Herring 1995; Garzanti 1993; Veevers & Tewari 1995) and oil source rocks of the Carnarvon and Canning Basins (Warris 1993) along this northern coast of Gondwana may have had an upwelling origin. Climate modelling confirms suitable conditions for offshore Ekman transport (that is, coast-parallel westerly winds) during the winter season (Kutzbach & Ziegler 1993). The fact that coals are lacking from the coastal sequences adjacent to these deposits implies dry climates for these mid-latitude regions, a likely corollary of upwelling conditions. We note that the Gondwanan coals are abundant elsewhere in India and Australia.

Amazon, Maranhao and Gabon Basins. We reconstruct these three basins as one continuous basin across Brazil to coastal Africa. This subtropical region shows extensive evaporites and eolianites in the early Permian intervals (Szatmari et al. 1979). In Gabon, earliest Permian tillites are followed by phosphorites, organic rich shales and finally evaporites (Micholet et al. 1970). Because of the quasi-marine nature of these deposits, a connection through the Amazon Basin is proposed as the most parsimonious connection to the ocean, bearing in mind that mid-Palaeozoic marine deposits are known from the intermediate areas in eastern Brazil. Early Permian source rocks are manifest in the areas of western South America, near the western end of the Amazon basin (Fernandez-Seveso & Tankard 1995; Mathalone & Montoya 1995), and we relate these to the cool subtropical upwelling system.

Arabian Basin. Tillites and dropstones extend through the first three intervals of the Permian and represent the lowest latitude of such deposits in the Permian, about 35° from the Equator (Ziegler et al. 1997). This region makes the transition from glacial and temperate conditions to the subtropical dry zone during the Permian. Thus, carbonate build-ups appear here about the time they disappear from the Northern Hemisphere (LeNindre et al. 1990).

South China Platform. This broad epeiric region moved across the Equator during the Permian. Coal is especially well developed during several stages and represents the passage beneath the Intertropical Convergence Zone (Nie 1991). The Cathaysian Floras have been related to the tropical rainforest biome (Ziegler 1990) and are equivalent in age to oil source rocks occurring in offshore basins. We relate these to brackish water-induced stratification of the water column (Wang & Ziegler, in prep.). Evaporites are not present but dolomites do occur in the southwest in the early Permian, and in the northeast in the latest Permian. These represent drier conditions and elevated salinities beneath the southern and northern subtropics, respectively, as the continent moved northward across the equatorial zone.

Western North America. This broad region extends from the Marathon thrust belt extension of the Appalachians on the southern margin of the Permian Basin of west Texas (Hanson 1991), across the Ancestral Rockies to the marginal basins of the Pacific Northwest. Early in the Permian the oil source rocks of west Texas seem to have formed in a 'Pontic Sea' (equivalent to the Present-day Black Sea; Hills 1972), while the floras indicate tropical wet conditions to the south and east (Ziegler 1991). We envisage a rapid transition from brackish conditions on the south to normal salinities in the region of the carbonate build-ups of the Texas–New Mexico border region and finally to the high salinities of the Denver and Williston Basins (Mazullo 1995). As the continent moved northward into the subtropics, progressively drier conditions enveloped the entire region as signalled by extensive evaporites and aeolian sand seas (Parrish & Peterson 1988). Along the Pacific rim, the Phosphoria Formation, with its oil source rocks, was deposited in upwelling conditions, as has been understood for many years (Claypool et al. 1984; Maughan 1994).

Zechstein Basin. Europe moved northward off the Equator in the Permian, so the tropical rainforests of the Carboniferous were left behind, with just a few coals remaining in the early Permian (Glennie 1984). The classic marine evaporite basin, the Zechstein Sea, developed in the late Permian of northern Europe (Figs 11, 12) as a successor to the non-marine Rotliegend evaporite basin (Fig. 10). Deep conditions existed, especially after the Zechstein was initially filled in a catastrophic flood (Kiersnowski et al. 1995) and oil source rocks developed during restricted intervals (Taylor 1984).

Russian Platform, and the Barents and Sverdrup Basins. The eastern margin of the Russian Platform was progressively thrust-loaded during the Permian. A deep foreland basin was present along this margin in the early Permian with a continuous line of reefs along its western side (Chuvashov 1983). Phosphorites occur in this basin (Ilyin 1989) which was of unknown width, so their apparent proximity to the reefs on our maps is probably spurious. The reef trend continues to the south around the perimeter of the North Caspian Depression (Aksenov 1993; Volchegurskiy et al. 1995) and to the north into the Pechora, Barents and Sverdrup Basins (Belyakov 1995; Bruce & Toomey 1993; Beauchamp 1993). This barrier reef trend apparently restricted oceanic exchange with the Russian Platform Seas, and evaporitic conditions were extensive, particularly in the Kungurian Stage (Fig. 7). Oil source rocks were deposited in the North Caspian Depression in the early Permian (Medvedeva et al. 1994), probably as a result of the silled nature of the basin; an additional factor could have been the development of a fresh water cap derived from runoff from the mountains to the south. The Uralian foreland basin was infilled with clastics during the late Permian, and these range from dry climate red beds in the central Urals to coals of the Wet Temperate zone in the northern Urals.

Omolon and the Verkhoyansk Coast. The Siberian part of Pangaea drifted from about 75° north to the pole during the Permian. A marine diamictite, the Atkan Formation, is widespread in this region and was originally interpreted as a deposit of beach-derived pebbles transported into relatively deep marine environments through the action of seasonal shore ice (Epshteyn 1981). More recently, 'pebbles and boulders with occasional traces of long-term glacier abrasion' have been discovered in this formation so glaciers must have developed and flowed into the sea at least locally (Chumakov 1994). The age is thought to be early Tatarian (Fig. 10) because the deposit seems to just predate the earliest 'normal' intervals of the magnetostratigraphic scale (Kashik 1990). The brachiopods of this horizon suggest an even earlier Kazanian age (T. A. Grunt, pers. comm.). In any case, a Middle Permian age is indicated and this means that this event is unlikely to have influenced the end-Permian extinction (cf. Knoll et al. 1996). Permian continental and marine strata of the Verkhoyansk margin of Siberia contain large amounts of humic matter and constitute a major source of both oil and gas (Sokolov et al. 1988). Land plant productivity is implicated and the timing of its deposition within the Permian is unclear.

CONCLUSIONS

We have compiled a Present-day water mass map based on a polyglot of oceanographic parameters and have correlated the result with sediment types potentially indicative of temperature, salinity and organic productivity. Thus, the water masses are based on rigorously defined contours of temperature and salinity which, admittedly, are only casually related to convergences and divergences in the surface currents of the oceans. The application of this approach to the geological past depends on the degree to which the climate-sensitive indicators match the water masses as defined. We have seen that these sediment types are rarely confined to one water mass category, and that they seem to be more concentrated in seaways with some geographic or bathymetric limitation from open ocean conditions. Since the continental shelves today average just 100 km in width, wider re-entrants like the Baltic Sea and the Persian Gulf become the models for the epeiric seas of the past.

In practice, we have found it relatively straightforward to reconstruct the water masses of the Permian, using the sediment indicators, and feel that an important test of the maps would be the extent to which they correlate with the biogeographic patterns of various fossil groups. Worldwide compilations based on a number of fossil groups have been published (see papers in Scholle et al. 1995, for good examples, and Grunt & Shi 1997), although an integration across all marine groups has never been attempted. Latitude (temperature) is often implied as a controlling factor in the Permian and the existence of a north–south

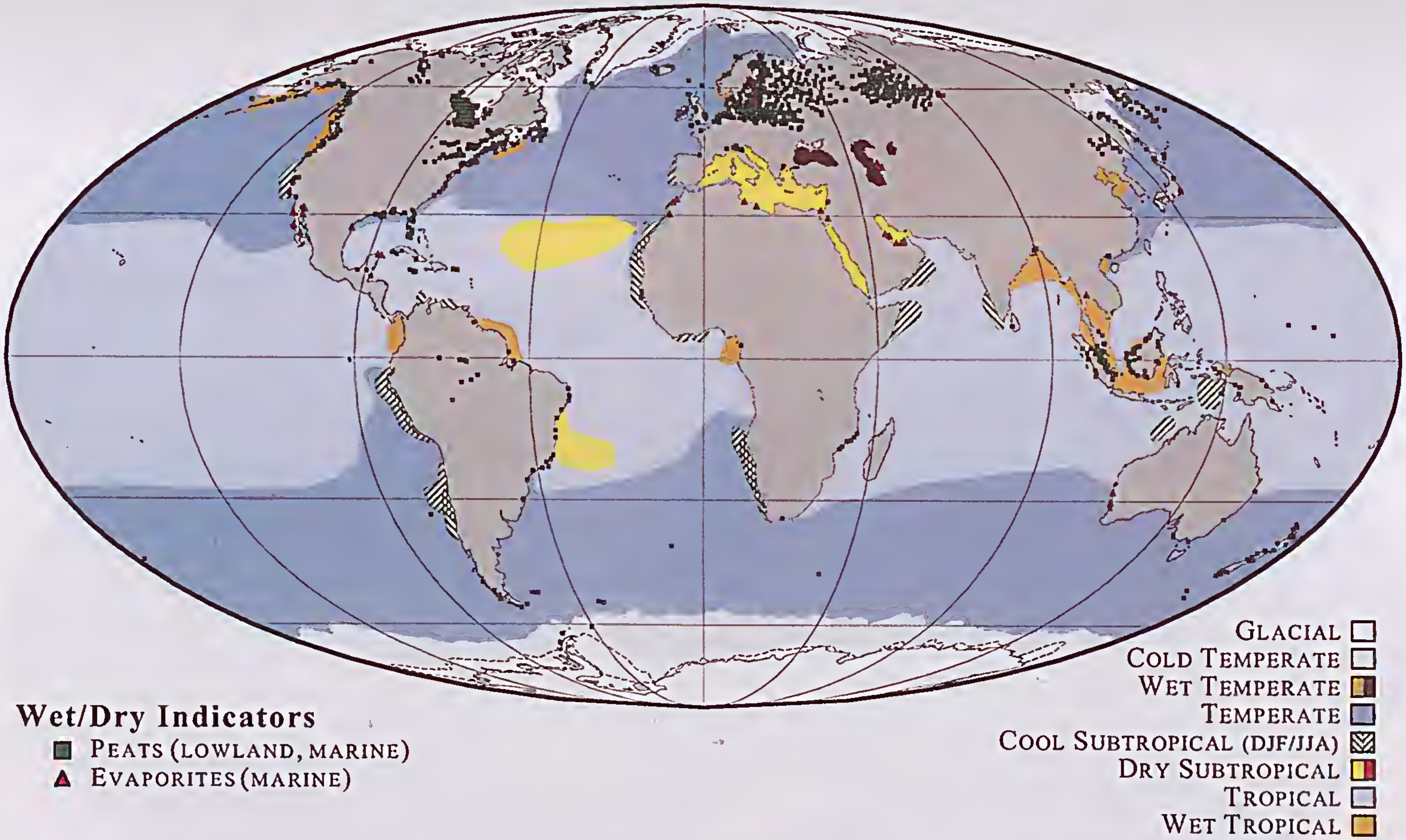

Fig. 1. Present-day indicators of precipitation balance superimposed on water mass patterns. Lowland peat deposits and marginal marine evaporites are plotted and may be compared with the low- and high-salinity areas, respectively. The water masses defined on relative salinity are the Wet Temperate and Wet Tropical zones (tan color = 27–32‰; brown = <27‰) and the Dry Subtropical zone (yellow color = 37–42‰; red = >42‰).

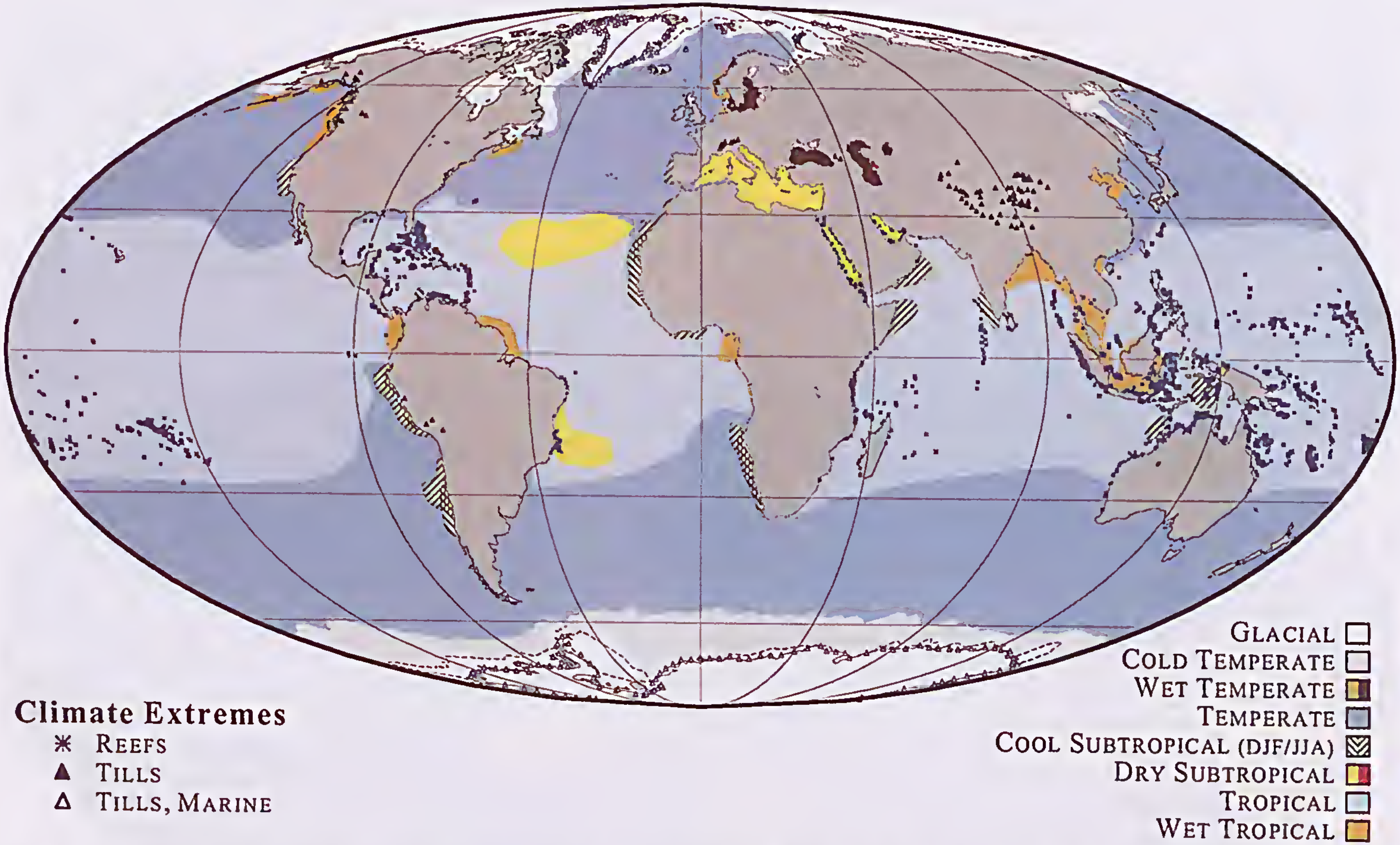

Fig. 2. Present-day indicators of climate extremes superimposed on water mass patterns. Reefs and tills are plotted and may be compared with the equatorial and polar water masses, respectively. The water masses defined on temperature are the Tropical and Dry Subtropical zones (>20°C) and the Cold Temperate and Glacial zones (<0°C). Winter conditions are shown in both hemispheres, as these are likely to be limiting for marine organisms.

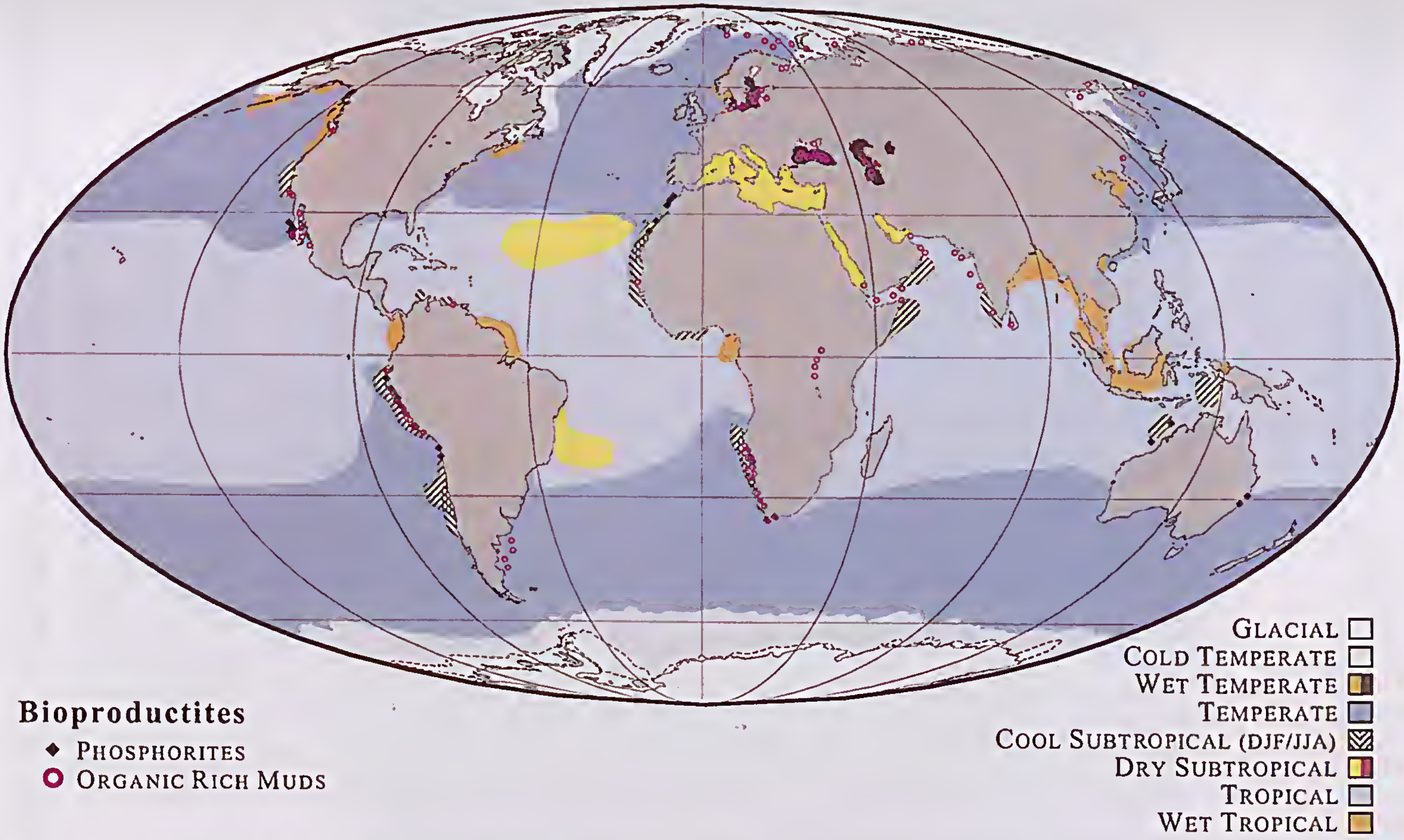

Fig. 3. Present-day indicators of high biological productivity superimposed on water mass patterns. Phosphorites and organic rich muds are plotted and may be compared with the Cool Subtropical and the Wet Temperate water masses. The upwelling regions define the Cool Subtropical zone and are shown for opposite seasons (DJF and JJA).

land barrier evokes the Present-day style of pervasive geographic barrier to marine interchange. We feel that the application of the water mass concept to biogeography and palaeobiogeography would help to stress the importance of salinity and productivity, in addition to temperature and

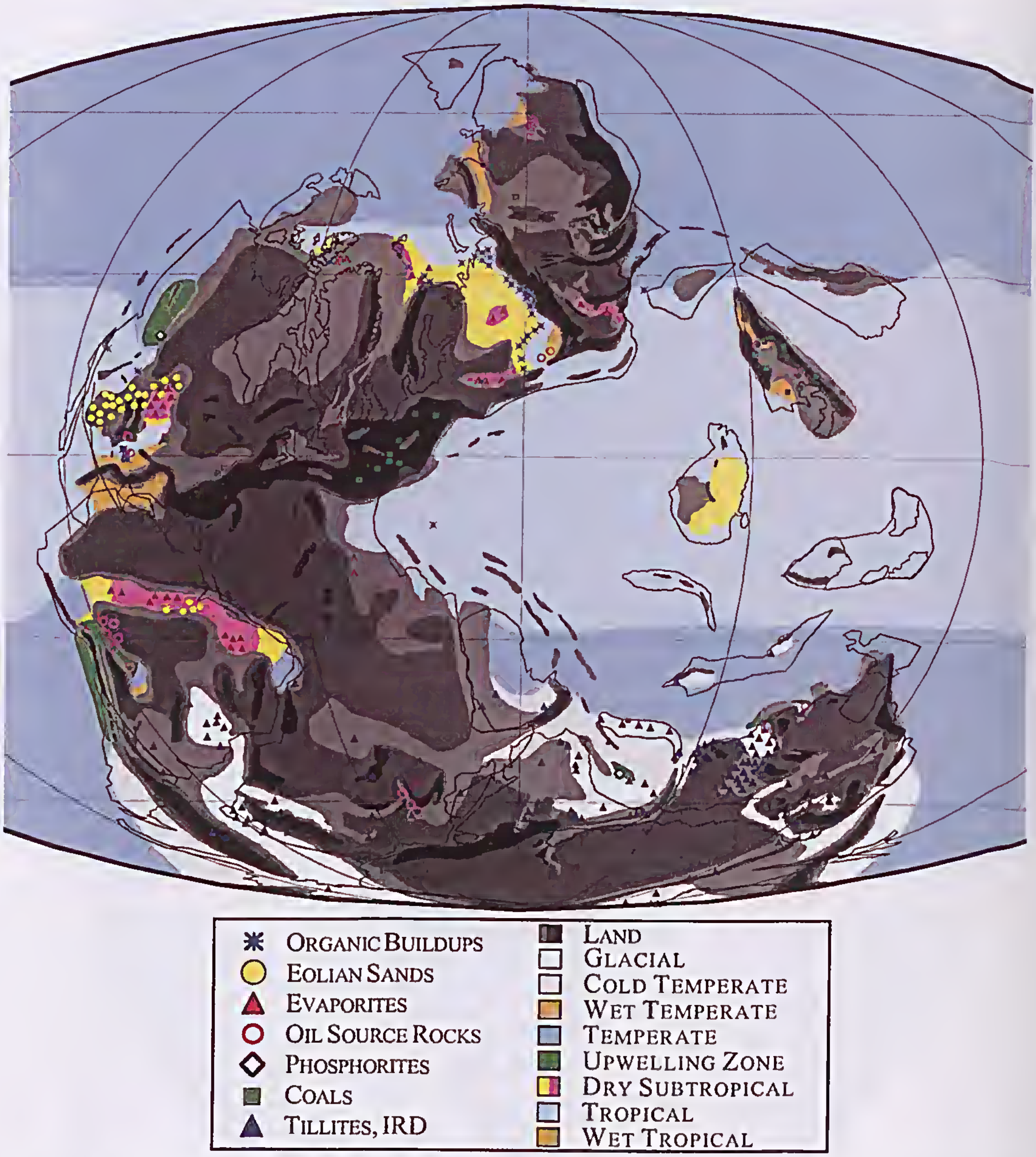

Fig. 4. Permian Stage 1 (Asselian, Early Wolfcampian, Early Chuanshanian) climate-sensitive sediments and reconstructed water masses. The palaeogeography is from the Sakmarian map of Ziegler et al. (1997).

geography. With this approach we can provide the geographic and climatic framework for examining evolutionary relationships of marine faunas, and to assess palaeontological arguments for distance between, or proximity of, terranes based on faunal differences or similarities.

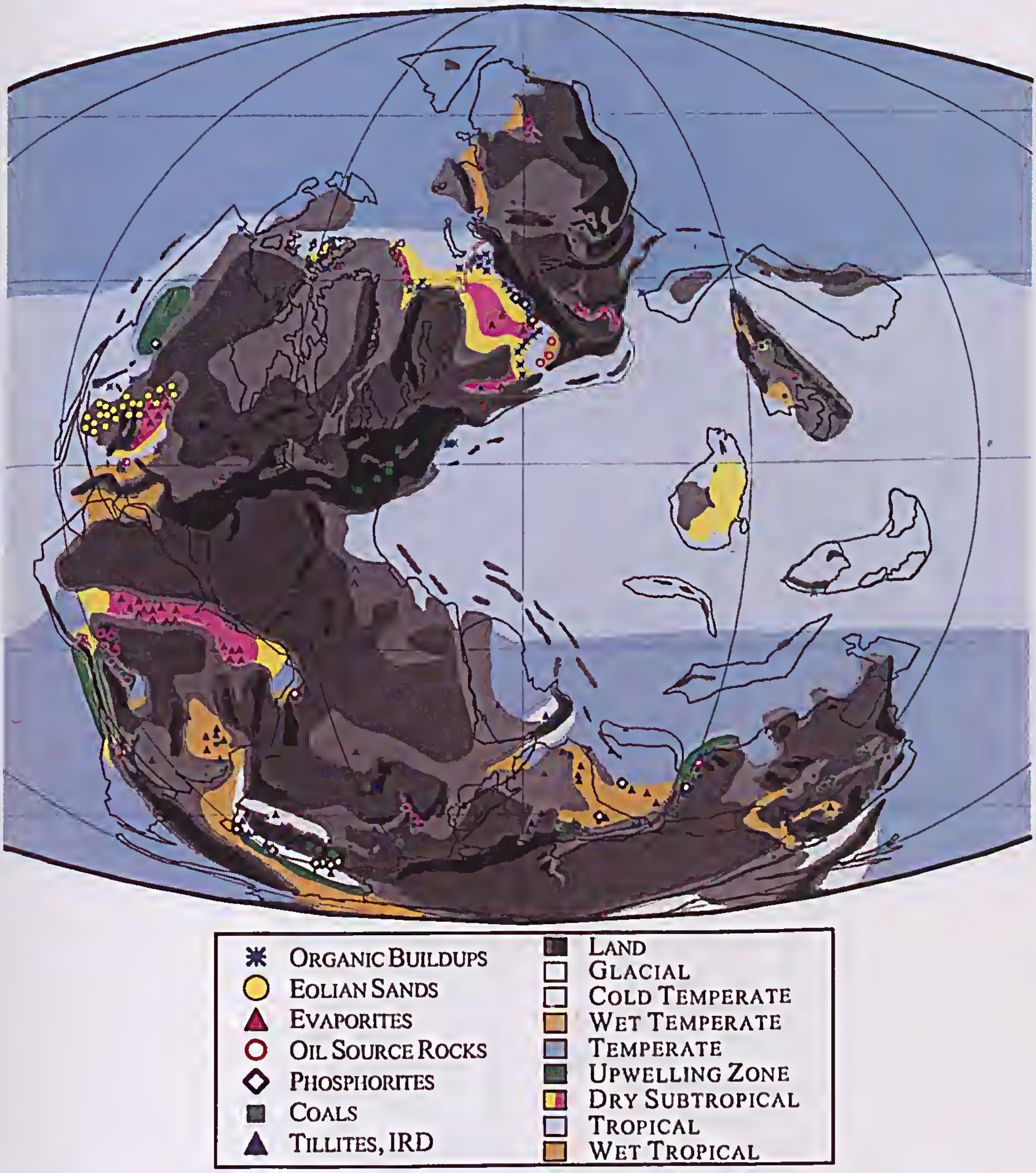

Fig. 5. Permian Stage 2 (Sakmarian, Late Wolfcampian, Middle Chuanshanian) climate-sensitive sediments and reconstructed water masses. The palaeogeography is from the Sakmarian map of Ziegler et al. (1997).

The effect of relative salinity on marine circulation is especially important because of its influence on the stratification versus mixing of the water column. Coal-forming swamps in the coastal regions are suggestive of the continuity of precipitation through the annual cycle (Lottes &

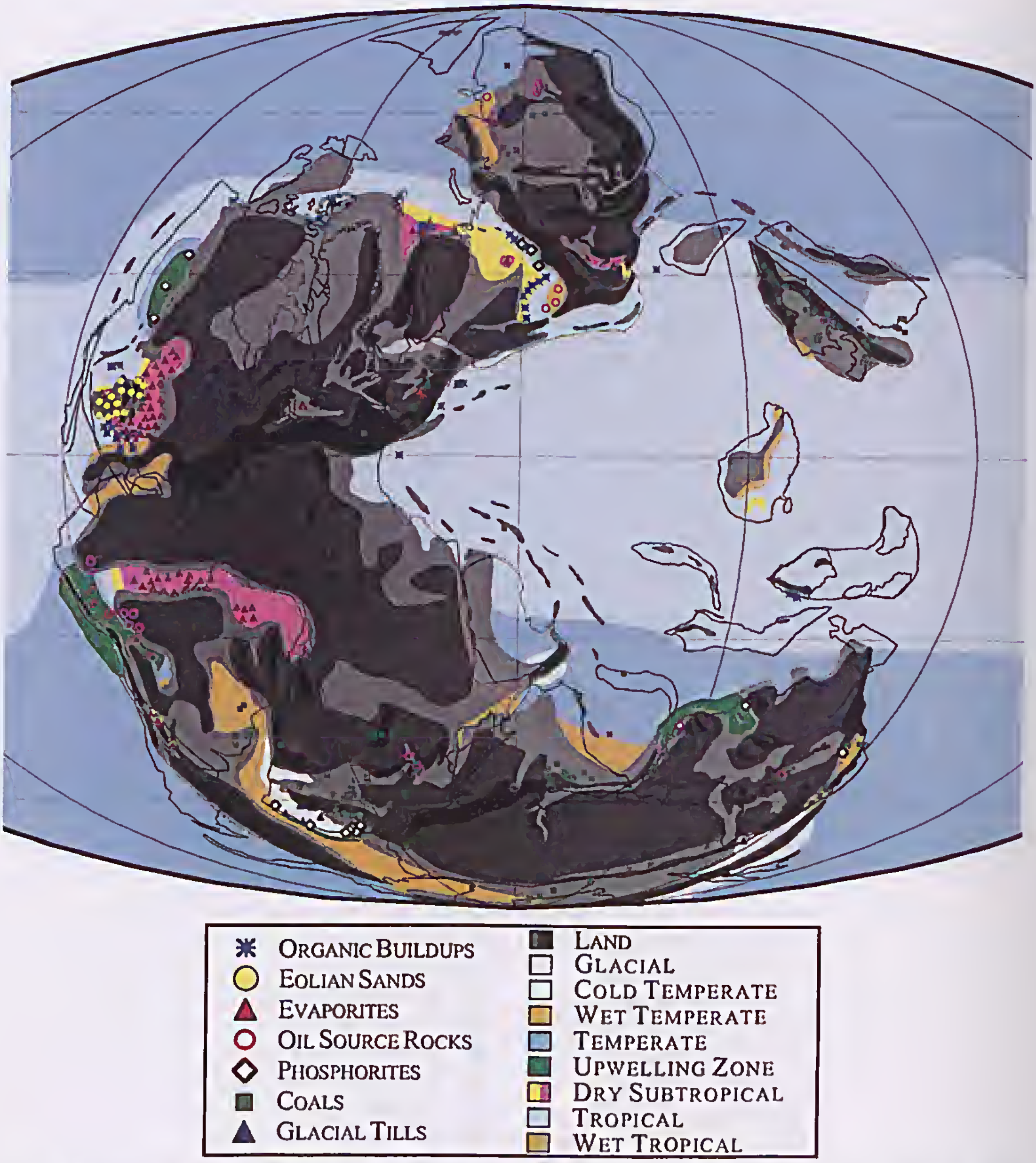

Fig. 6. Permian Stage 3 (Artinskian, Early Leonardian, Late Chuanshanian) climate-sensitive sediments and reconstructed water masses. The palaeogeography is from the Artinskian map of Ziegler et al. (1997).

Ziegler 1994) and therefore of fresh-water runoff and stratified water masses. Clastic and nutrient input as well as turbidity are also implied, given suitable source areas, so pelagic communities and organic-rich muds should dominate in end-member examples of these low salinity water masses.

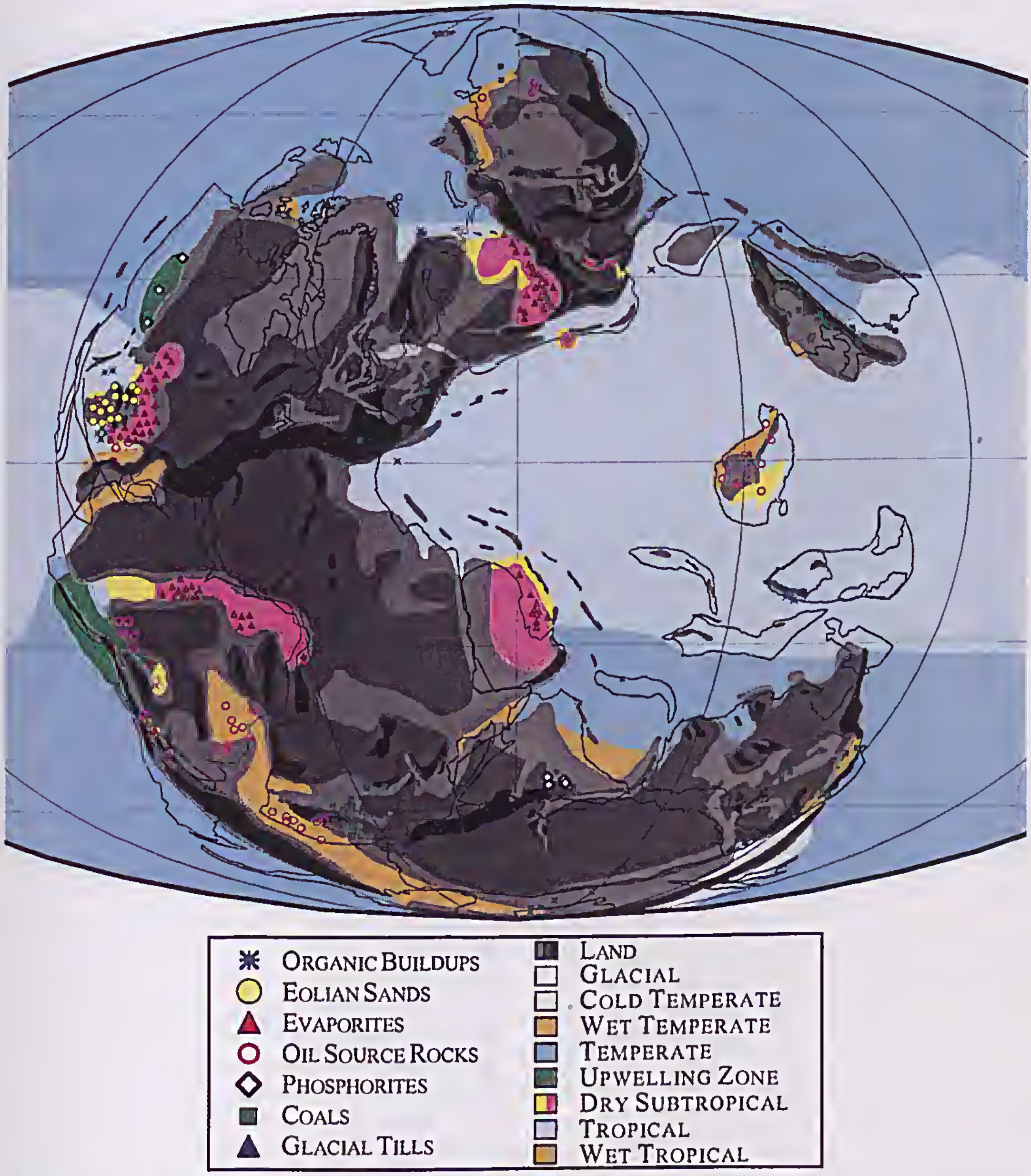

Fig. 7. Permian Stage 4 (Kungurian, Late Leonardian, Early Chihsian) climate-sensitive sediments and reconstructed water masses. The palaeogeography is from the Artinskian map of Ziegler et al. (1997).

Examples include the middle to late Permian of China and the late Carboniferous to earliest Permian of the US Midcontinent. At the opposite end of the spectrum are the evaporite basins so prominent in the Permian, including the Zechstein, Russian and US seaways of the northern subtropical zone,

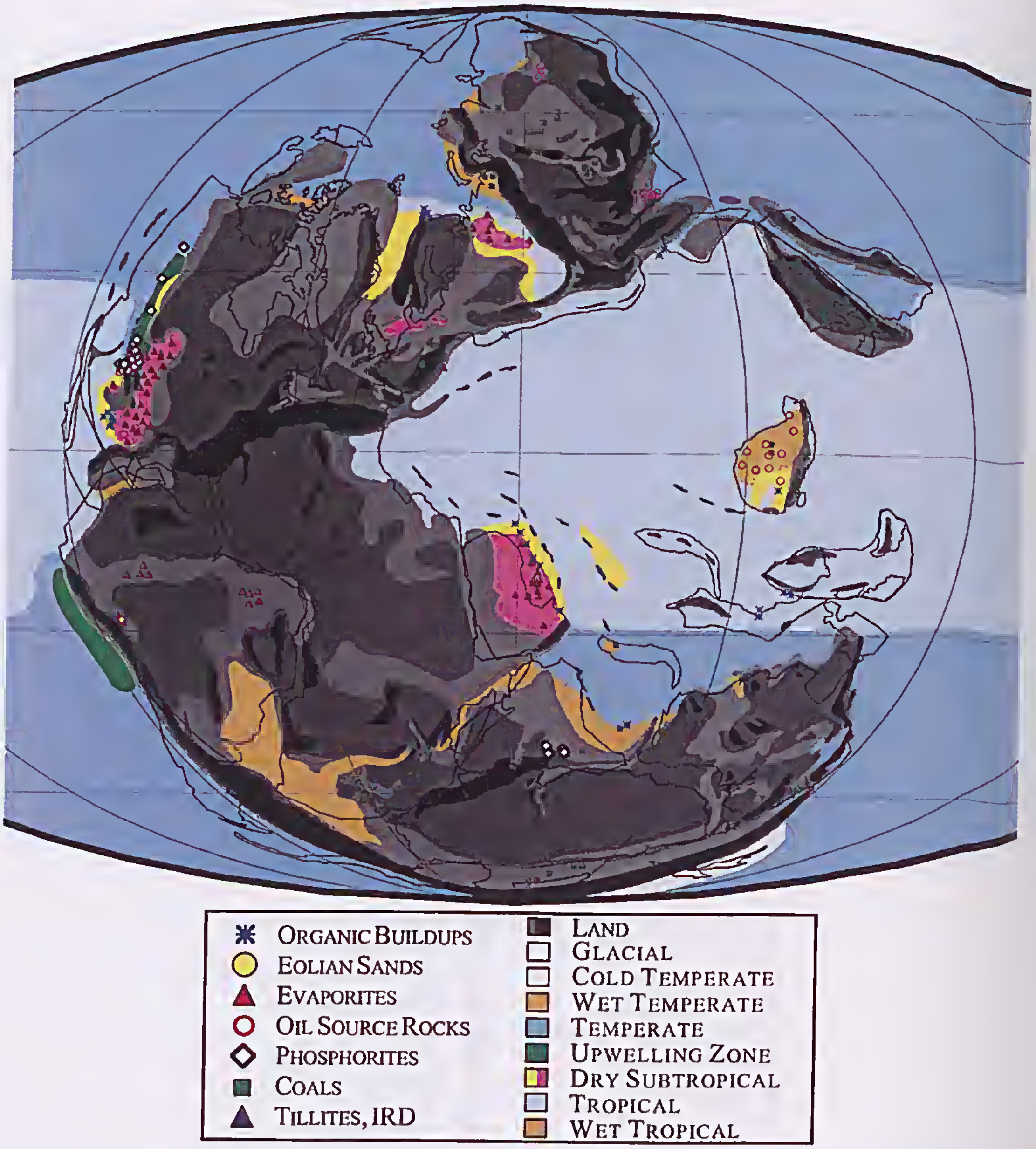

Fig. 8. Permian Stage 5 (Ufimian, Roadian, Late Chihsian) climate-sensitive sediments and reconstructed water masses. The palaeogeography is from the Kazanian map of Ziegler et al. (1997).

and the Amazon and Arabian Basins of the opposite hemisphere. These basins must have had a deficiency of precipitation in relation to evaporation and a well-mixed water column; faunas were extremely specialised and limited by the high salinities and temperatures.

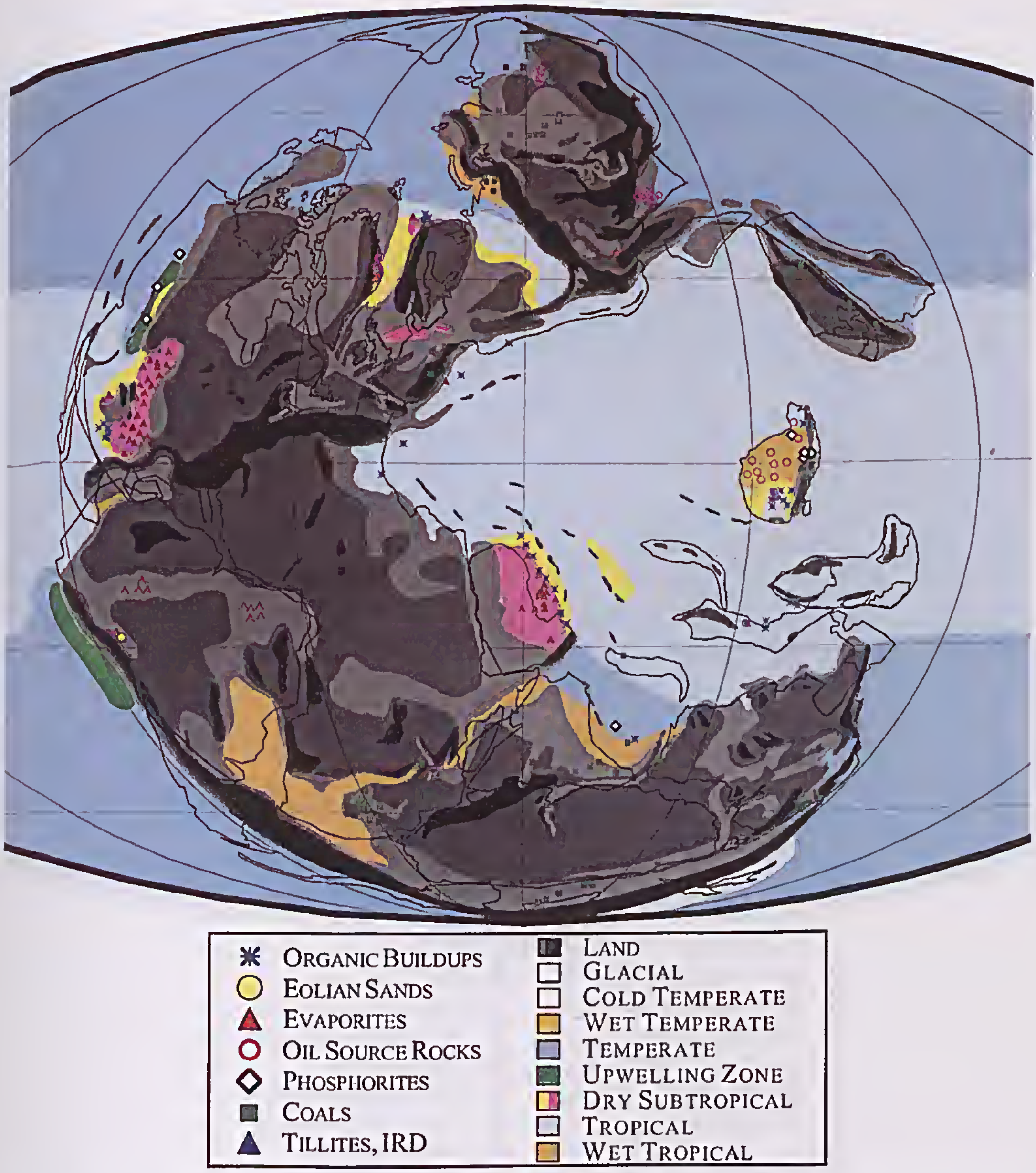

Fig. 9. Permian Stage 6 (Kazanian, Wordian, Early Maokouan) climate-sensitive sediments and reconstructed water masses. The palaeogeography is from the Kazanian map of Ziegler et al. (1997).

Finally, oil source rocks are widespread in Permian rocks and originated in a variety of environments. These include lakes and coal swamps in the terrestrial realm, density-stratified basins in the marine realm, and coastal upwelling zones. Authors have favoured the upwelling model for

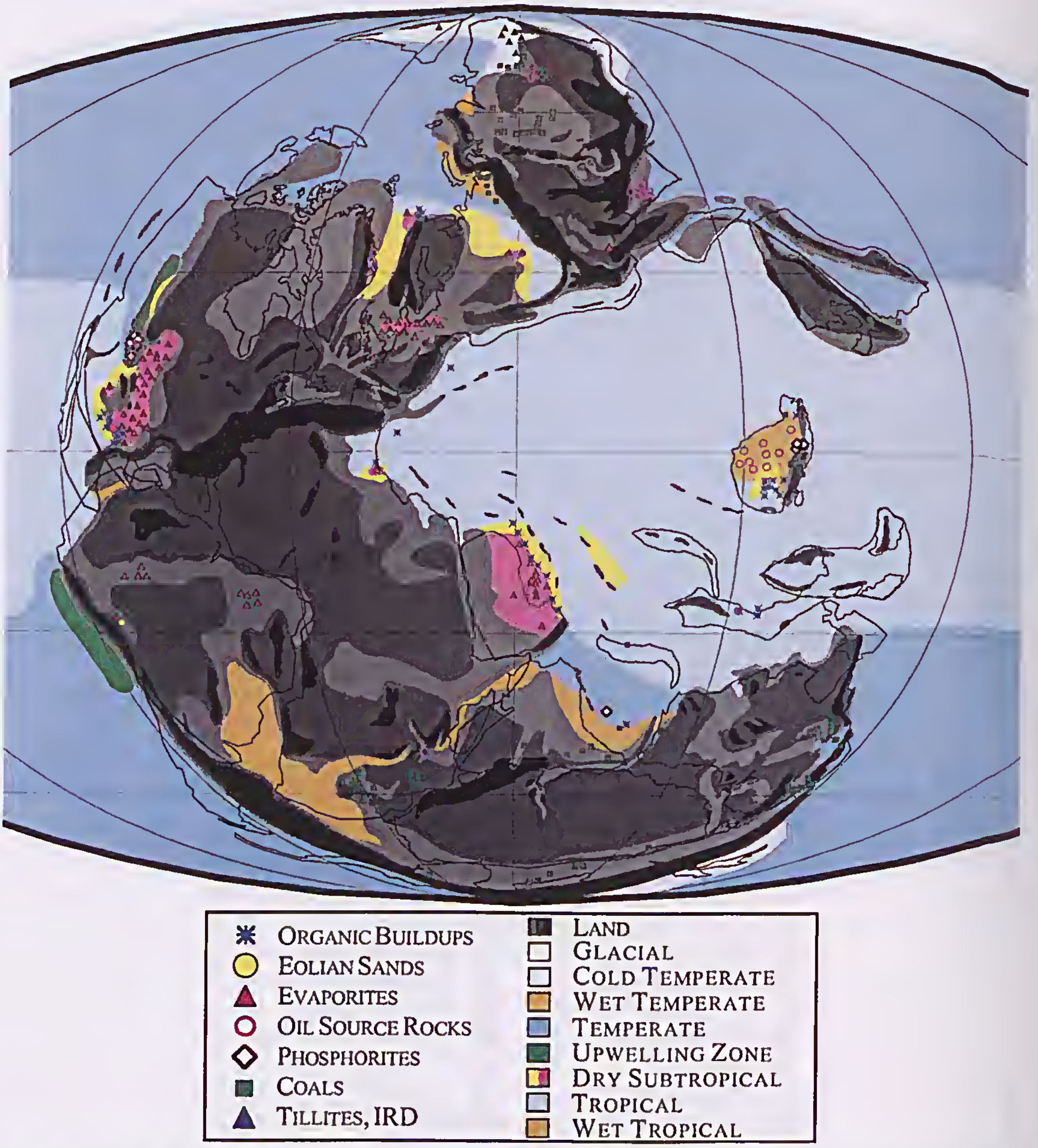

Fig. 10. Permian Stage 7 (Early Tatarian, Capitanian, Late Maokouan) climate-sensitive sediments and reconstructed water masses. The palaeogeography is from the Tatarian map of Ziegler et al. (1997).

marine source rocks (Parrish 1995; Hay 1995), but many Permian oil basins are associated with sediment types that are inconsistent with the upwelling setting. These include coals and other indicators of rainfall, while in fact desert conditions are typical around upwelling zones because the

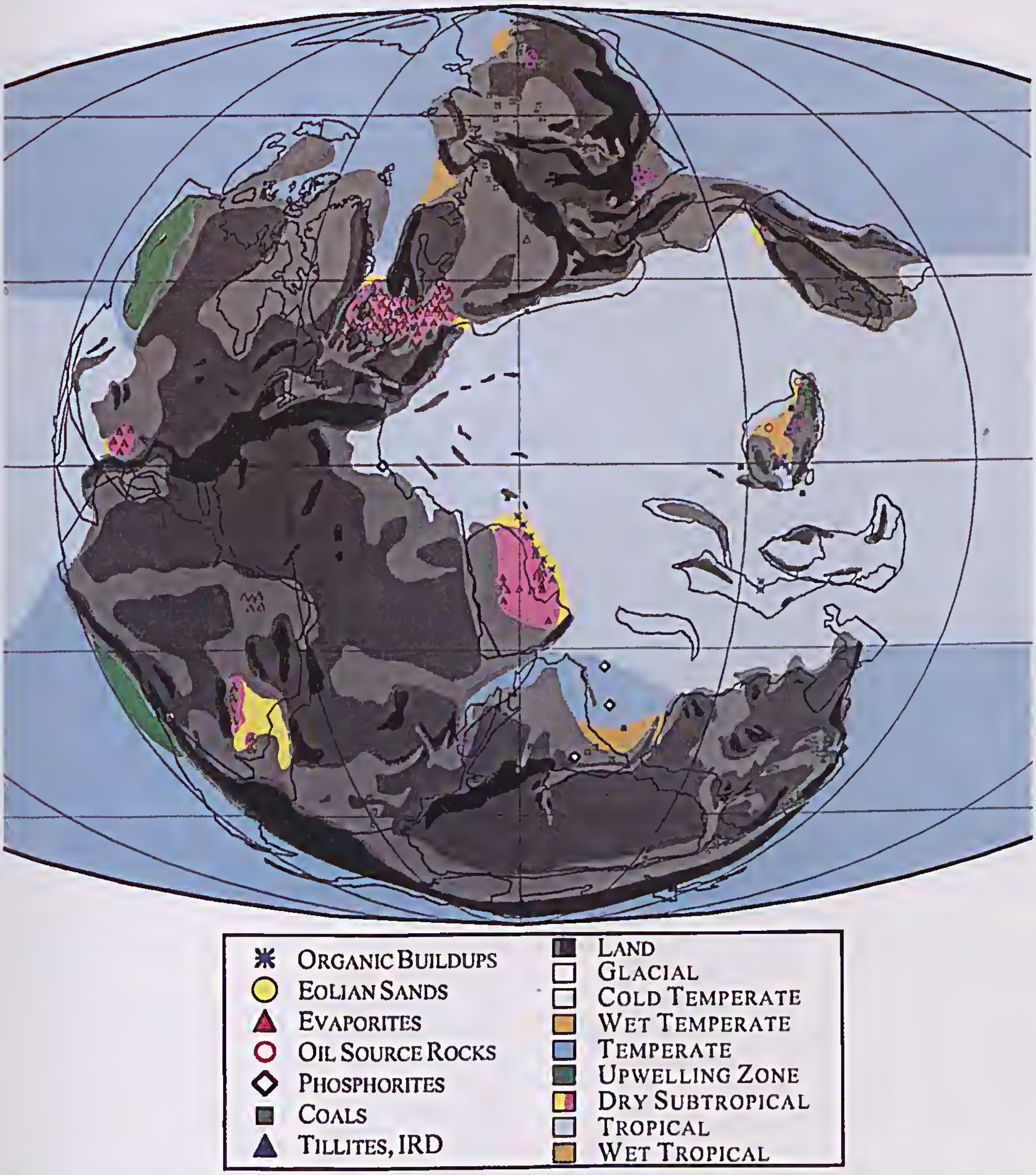

Fig. 11. Permian Stage 8 (Middle Tatarian, Early Ochoan, Wuchiapingian) climate-sensitive sediments and reconstructed water masses. The palaeogeography is from the Tatarian map of Ziegler et al. (1997).

cool waters inhibit evaporation and chill the atmosphere. Also, carbonate buildups are associated with a number of Permian oil forming basins (i.e. west Texas), and normally bottom productivity is inhibited by the opacity to light penetration that results from the plankton blooms of upwelling

Fig. 12. Permian Stage 9 (Late Tatarian, Late Ochoan, Changhsingian) climate-sensitive sediments and reconstructed water masses. The palaeogeography is from the Tatarian map of Ziegler et al. (1997).

zones. This work is thus allowing us to expand predictive models for these economically important deposits.

REFERENCES

Aksenov, A. A., Novikov, A. A. & Mikhalkova, V. N., 1993. Oil–gas prospects of the Volgograd Trans-Volga region. *Petroleum Geology* 27: 275–280.

Beauchamp, B., 1993. Carboniferous and Permian reefs of Sverdrup Basin, Canadian Arctic: an aid to Barents Sea exploration. In *Arctic Geology and Petroleum Potential*, T. O. Vorren et al., eds, Norwegian Petroleum Society Special Publication 2, Elsevier, Amsterdam, 217–241.

Belyakov, S. L., 1995. Lower Permian paleostructural units of the Timan–Pechora region. *Geotectonics* 28: 33–43.

Binet, D. & Marchal, E., 1993. The large marine ecosystem of shelf areas in the Gulf of Guinea: long-term variability induced by climatic changes. In *Large Marine Ecosystems: Stress, Mitigation, and Sustainability*, K. Sherman, A. M. Alexander & B. D. Gold, eds, AAAS Press, Washington, DC, 104–118.

Briggs, J. C., 1974. *Marine Zoogeography*. McGraw-Hill, New York, 475 pp.

Bruce, J. R. & Toomey, D. F., 1993. Late Palaeozoic bioherm occurrences of the Finnmark Shelf, Norwegian Barents Sea: analogues and regional significance. In *Arctic Geology and Petroleum Potential*, T. O. Vorren et al., eds, Norwegian Petroleum Society Special Publication 2, Elsevier, Amsterdam, 377–392.

Buhmann, D., Buhmann, C. & von Brunn, V., 1989. Glaciogenic banded phosphorites from Permian sedimentary rocks. *Economic Geology and the Bulletin of the Society of Economic Geologists* 84: 741–750.

Chumakov, N. M., 1994. Evidence of Late Permian glaciation in the Kolyma River Basin: A repercussion of the Gondwana glaciations in northeast Asia? *Stratigraphy and Geological Correlation* 2: 130–150.

Chuvashov, B. I., 1984. Permian reefs of the Urals. *Facies* 8: 191–212.

Claypool, G. E., Love, A. H. & Maughan, E. K., 1984. Organic geochemistry, incipient metamorphism and oil generation in Black Shale Members of Phosphoria Formation, Western Interior United States. In *Petroleum Geochemistry and Basin Evaluation*, G. Demaison & R. J. Murris, eds, *American Association of Petroleum Geologists Memoir* 35: 139–158.

Cole, D. I. & McLachlin, I. R., 1991. Oil potential of the Permian Whitehill Shale Formation in the Main Karoo Basin, South Africa. In *Gondwana Seven Proceedings: Papers Presented at the Seventh International Gondwana Symposium*, R. Ulbrich & A. C. Rocha Campos, eds, 379–390.

Collinson, J. W., Varva, C. L. & Zawiskie, J. M., 1992. Sedimentology of the Polarstar Formation (Permian), Ellsworth Mountains, West Antarctica. *Geological Society of America Memoir* 170: 63–79.

Demaison, G. J. & Moore, G. T., 1980. Anoxic environments and oil source bed genesis. *American Association of Petroleum Geologists Bulletin* 64: 1179–1209.

Dickins, J. M., 1996. Problems of a Late Palaeozoic glaciation in Australia and subsequent climate in the Permian. *Palaeogeography, Palaeoclimatology, Palaeoecology* 125: 185–197.

Epshteyn, O. G., 1981. Late Permian ice-margin deposits of the Atkan Formation of the Kolyma river headwaters region, U.S.S.R. In *Earth's Pre-Pleistocene Glacial Record*, M. J. Hambrey & W. B. Harland, eds, Cambridge University Press, Cambridge, 270–273.

Fernandez-Seveso, F. & Tankard, A. J., 1995. Tectonics and Stratigraphy of the Late Paleozoic Paganzo basin of western Argentina and its regional implications. In *Petroleum Basins of South America*, A. J. Tankard, R. Suárez S. & H. J. Welsink, eds, *AAPG Memoir* 62: 285–301.

Garzanti, E., 1993. Himalayan ironstones, 'superplumes', and the breakup of Gondwana. *Geology* 21: 105–108.

Glennie, K. W., 1984. Early Permian-Rotliegend. In *Introduction to the Petroleum Geology of the North Sea*, K. W. Glennie, ed., Blackwell Scientific Publishers, Oxford, 41–60.

Gordon, A. L., 1967. Circulation of the Caribbean Sea. *Journal of Geophysical Research* 72: 6207–6223.

Grunt, T. A. & Shi, G. R., 1997. A Hierarchical framework of Permian global marine biogeography. In *Palaeontology and Historical Geology*, Jin Yugan & D. Dineley, eds, *Proceedings of the 30th International Geological Congress*, vol. 12, VSP, Utrecht, The Netherlands, 2–17.

Hanson, B. M., Powers, B. K., Garrett, C. M. Jnr, McGookey, D. E., McGlasson, E. H., Horak, R. L. et al., 1991. The Permian basin. In *Economic Geology, U.S.*, H. J. Gluskoter et al., eds, The Geology of North America, Vol. P-2, Geological Society of America, Boulder Colorado, 339–356.

Hay, W. H., 1995. Paleoceanography of marine-organic-rich sediments. In *Paleogeography, Paleoclimate, and Source Rocks*, A. Y. Hue, ed., *AAPG Studies in Geology* 40: 21–59.

Herring, J. R., 1995. Permian phosphorites: a paradox of phosphogenesis. In *The Permian of Northern Pangea, Vol. 2: Sedimentary Basin and Economic Resources*, P. A. Scholle, T. M. Peryt & D. S. Ulmer-Scholle, eds, Springer-Verlag, Berlin, 292–312.

Hills, J. M., 1972. Late Paleozoic sedimentation in west Texas Permian Basin. *American Association of Petroleum Geologists Bulletin* 56: 2303–2334.

HULVER, M. L., ZIEGLER, A. M., ROWLEY, D. B. & GIBBS, M. T., 1997. Global latitudinal distribution of Permian to Recent climate-sensitive sediments, *Geological Society of America Abstracts with Programs* 29: 6.

ILYIN, A. V., 1989. Permian phosphorites of the Ural Mountains, USSR. In *Phosphate Deposits of the World*, vol. 2, A. J. G. Notholt, R. P. Sheldon & D. F. Davidson, eds, Cambridge University Press, Cambridge, 503–506.

ITTEKOT, V., HAAKE, B., BARTSCH, M., NAIR, R. R. & RAMASWAMY, V., 1992. Organic carbon removal in the sea: The Continental Connection. In *Upwelling Systems: Evolution Since the Miocene*, C. P. Summerhayes, W. L. Prell & K. C. Emeis, eds, *Geological Society Special Publication* No. 64: 167–176.

JIN, Y.-G., WARDLAW, B. R., GLENISTER, B. F. & KOTLYAR, G. V., 1997. Permian chronostratigraphic subdivisions. *Episodes* 20: 10–15.

KASHIK, D. S., 1990. *Permian key section of the Omolon Massif.* Nauka Publishers, Leningrad, 198 pp.

KIERSNOWSKI, H., PAUL, J., PERYT, T. M. & SMITH, D. B., 1995. Facies, paleogeography, and sedimentary history of the Southern Permian Basin in Europe. In *The Permian of Northern Pangea, Vol. 2: Sedimentary Basins and Economic Resources*, P. A. Scholle, T. M. Peryt & D. S. Ulmer-Scholle, eds, Springer-Verlag, Berlin, 119–136.

KNOLL, A. H., BAMBACH, R. K., CANFIELD, D. E. & GROTZINGER, J. P., 1996. Comparative earth history and Late Permian mass extinction. *Science* 273: 452–457.

KUTZBACH, J. E. & ZIEGLER, A. M., 1993. Simulation of Late Permian climate and biomes with an atmosphere-ocean model: Comparisons with observations. *Philosophical Transactions of the Royal Society of London*, Series B 341: 327–340.

LE NINDRE, Y.-M., MANIVIT, J. & VASLET, D., 1990. Géodynamique et Paléogéographie de la Plateforme Arabe du Permien au Jurassique. *Histoire Géologique de la Bordure Occidentale de la Plateforme Arabe* 2, Éditions du BRGM, Orleans, France, 280 pp.

LOTTES, A. L. & ZIEGLER, A. M., 1994. World peat occurrence and the seasonality of climate and vegetation. In *The Euramerican Coal Province: Controls on Tropical Peat Accumulation in the Late Paleozoic. Palaeogeography, Palaeoclimatology, Palaeoecology* 106: 23–37.

MANN, K. H. & LAZIER, J. R. N., 1991. *Dynamics of Marine Ecosystems: Biological–Physical Interactions in the Oceans.* Blackwell Scientific Publications, Oxford, 466 pp.

MATHALONE, J. M. P. & M. MONTOYA, R., 1995. Petroleum geology of the sub-Andean basins of Peru. In *Petroleum Basins of South America*, A. J. Tankard, R. Suárez S. & H. J. Welsink, eds, *AAPG Memoir* 62: 423–444.

MAUGHAN, E. K., 1994. Phosphoria Formation (Permian) and its resource significance in the western interior, U.S.A. In *Pangea: Global Environments and Resources*, A. F. Embry et al., eds, *Canadian Society of Petroleum Geologists Memoir* 17: 479–496.

MAZZULO, S. J., 1995. Permian stratigraphy and facies, Permian Basin (Texas–New Mexico) and adjoining areas in the Midcontinent United States. In *The Permian of Northern Pangea, Vol. 2: Sedimentary Basins and Economic Resources*, P. A. Scholle, T. M. Peryt & D. S. Ulmer-Scholle, eds, Springer-Verlag, Berlin, 41–60.

MEDVEDEVA, A. M., BULEKBAYEV, Z. Y. & DAL'YAN, I. B., 1994. Direct indications of vertical migration of oil in east of north Caspian depression. *Petroleum Geology* 28: 243–248.

MICHOLET, J., MOLINAS, E. & PENET, B., 1970. Le systeme du Karroo au Gabon. In *Second Gondwana Symposium, South Africa, 1970, Proceedings and Papers*, S. H. Haughton, ed., Council for Scientific and Industrial Research, Scientia, Pretoria, South Africa, 371–377.

NELSON, C. S., 1988. An introductory perspective on non-tropical shelf carbonates. *Sedimentary Geology* 60: 3–12.

NEWELL, N. D. & RUNNEGAR, B., 1970. Endemic Permian molluscan fauna in the Parana Basin of South America. In *Second Gondwana Symposium, South Africa, 1970, Proceedings and Papers*, S. H. Haughton, ed., Council for Scientific and Industrial Research, Scientia, Pretoria, South Africa, 613–614.

NIE, S., 1991. Paleoclimatic and paleomagnetic constraints on the Paleozoic reconstructions of south China, north China and Tarim. In *Accretionary Tectonics and Composite Continents*, R. D. Hatcher Jnr & L. Zonenshain, eds, *Tectonophysics* 196: 279–308.

OELOFSEN, B. & ARAUJO, D. C., 1983. Palaeoecological implications of the distribution of mesosaurid reptiles in the Permian Irati Sea (Parana Basin), South America. *Revista Brasileira de Geociencias* 13: 1–6.

PARKINSON, C. L., COMISO, J. C., ZWALLY, H. J., CAVALIERI, D. J., GLOERSEN, P. & CAMPBELL, W. J., 1987. *Arctic Sea Ice, 1973–1976.* NASA, Washington, DC, 296 pp.

PARRISH, J. T., 1982. Upwelling and petroleum source beds, with reference to the Paleozoic. *American Association of Petroleum Geologists Bulletin* 66: 750–774.

PARRISH, J. T., 1995. Paleogeography of C_{org}-rich rocks and the preservation versus production controversy. In *Paleogeography, Paleoclimate, and Source Rocks*, A. Y. Huc, ed., *AAPG Studies in Geology* 40: 1–20.

PARRISH, J. T. & PETERSON, F. 1988. Wind directions predicted from global circulation models and wind directions determined from eolian sandstones of the western United States—a comparison. *Sedimentary Geology* 56: 261–282.

PARRISH, R. H., BAKUN, A., HUSBY, D. M. & NELSON, C. S., 1983. Comparative climatology of selected environmental processes in relation to Eastern Boundary Current pelagic fish reproduction. In *Proceedings of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources. San Jose, Costa Rica, 18–29 April 1983*, G. D. Sharp & J. Csirke, eds, FAO Fisheries Report No. 291, vol. 3, United Nations, Rome, 731–777.

RETALLACK, G. J., 1980. Late Carboniferous to Middle Triassic megafossil floras from the Sydney Basin. In *A guide to the Sydney Basin*, C. Herbert & R. J. Helby, eds, *Geological Survey of New South Wales Bulletin* 26: 384–430.

SCHOLLE, P. A., PERYT, T. M. & ULMER-SCHOLLE, D. S., eds, 1995. *The Permian of Northern Pangea, Vol. 1: Paleogeography, Paleoclimates. Stratigraphy*, Springer-Verlag, Berlin, 261 pp.

SHARMA, G. S., 1978. Upwelling off the southwest coast of India. *Indian Journal of Marine Sciences* 7: 209–218.

SHERMAN, K., 1993. Large marine ecosystems as global units for marine resources management—an ecological perspective. In *Large Marine Ecosystems: Stress, Mitigation, and Sustainability*, K. Sherman, L. M. Alexander & B. D. Gold, eds, AAAS Press, Washington, DC, 3–14.

SHI, G. R. & ARCHBOLD, N. W., 1996. A quantitative palaeobiogeographical analysis of the distribution of Sterlitamakian–Aktastinian (Early Permian) western Pacific brachiopod faunas. *Historical Biology* 11: 101–123.

SOKOLOV, B. A., 1988. History of oil–gas formation and accumulation in the east of the Siberian Craton. *Petroleum Geology* 23: 12–45.

SVERDRUP, H. U., JOHNSON, M. W. & FLEMING, R. H., 1942. *The Oceans: Their Physics, Chemistry, and General Biology*, Prentice Hall, New York, 1087 pp.

SZATMARI, P., CARVALHO, R. S. & SIMOES, I. A., 1979. A comparison of evaporite facies in the Late Paleozoic Amazon and the Middle Cretaceous South Atlantic salt basins. *Economic Geology* 74: 432–447.

TAYLOR, J. C. M., 1984. Late Permian–Zechstein. In *Introduction to the Petroleum Geology of the North Sea*, K. W. Glennie, ed., Blackwell Scientific Publications, Oxford, 61–83.

TOMCZAK, M. & GODFREY, J. S., 1994. *Regional Oceanography: An Introduction*. Pergamon, Oxford, 422 pp.

VAN ANDEL, T. H., 1964. Recent marine sediments of Gulf of California. In *Marine Geology of the Gulf of California*, T. H. van Andel & G. G. Shor, eds, *American Association of Petroleum Geologists Memoir* 3: 216–310.

VEEVERS, J. J. & TEWARI, R. C., 1995. *Gondwana Master Basin of Peninsular India between Tethys and the Interior of the Gondwanaland Province of Pangea.* Geological Society of America, Memoir 187, 72 pp.

VOLCHEGURSKIY, L. F., VLADIMIROVA, T. V., KAPUSTIN, I. N. & NATAPOV, L. M., 1995. Evolution of the North Caspian Depression in the Middle–Late Paleozoic. *Petroleum Geology* 29: 362–369.

WARRIS, B. J., 1993. The hydrocarbon potential of the Palaeozoic basins of western Australia. *APEA Journal* 33(1): 123–137.

ZALAN, P. V., WOLFF, S., ASTOLFI, M. A. M., VIERA, I. S., CONCELCAO, J. C. J., APPI, V. T. et al., 1991. The Paraná Basin, Brazil. In *Interior Cratonic Basins*, M. W. Leighton, D. R. Kolata, D. F. Oltz & J. J. Eidel, eds, *American Association of Petroleum Geologists Memoir* 51: 681–708.

ZIEGLER, A. M., 1990. Phytogeographic patterns and continental configurations during the Permian Period. In *Palaeozoic Palaeogeography and Biogeography*, W. S. McKerrow & C. R. Scotese, eds, *Geological Society of London Memoir* 12: 363–379.

ZIEGLER, A. M., 1998. *Warm polar currents.* EOS, Transactions, American Geophysical Union 78, Spring Meeting Supplement.

ZIEGLER, A. M., HULVER, M. L., LOTTES, A. L. & SCHMACHTENBERG, W. F., 1984. Uniformitarianism and palaeoclimates: Inferences from the distribution of carbonate rocks. In *Fossils and Climate*, P. J. Brenchley, ed., John Wiley & Sons Ltd, Chichester, 3–25.

ZIEGLER, A. M., HULVER, M. L. & ROWLEY, D. B., 1997. Permian world topography and climate. In *Late Glacial and Postglacial Environmental Changes*, I. P. Martini, ed., Oxford University Press, New York and Oxford, 111–146.

ZIJLSTRA, J. J. & BAARS, M. A., 1990. Productivity and fisheries potential of the Banda Sea ecosystem. In *Large Marine Ecosystems: Patterns, Processes and Yields*, K. Sherman, L. M. Alexander & B. D. Gold, eds, AAAS Press, Washington, DC, 54–65.

ZWALLY, H. J., COMISO, J. C., PARKINSON, C. L., CAMPBELL, W. J., CARSEY, F. D. & GLOERSEN, P., 1983. *Antarctic Sea Ice, 1973–1976.* NASA, Washington, DC, 206 pp.